FIG. 2B is a schematic view of another beam directing technique.

FIGS. 3, 3A, 3B, 3C and 3D are plots of beam energy density.

FIG. 4 is a schematic side view of a beam directing technique.

FIGS. 5, 6 and 6A are schematic side views of cleaning schemes.

FIG. 7 is a schematic sectional side view of a substrate being cleaned.

FIG. 8 is a plot of maximum energy density as a function of beam angle.

FIG. 9 is a plot of the maximum wafer scan rates.

FIG. 10 is a schematic top view of wafer regions illuminated by an array of laser beams.

FIG. 10A is a schematic side view of an optical system for producing an array of illuminated regions.

FIG. 10B is a schematic top view of a surface cleaning scheme.

FIG. 11 is schematic side view of a cleaning scheme.

FIG. 11A is a perspective view of a gas delivery system.

FIG. 12 is a schematic side view of a surface cleaning scheme.

FIG. 13 is a schematic side view of a wafer with an ion-implanted photoresist layer.

FIG. 14 is schematic side view of a cleaning scheme.

FIG. 15 is a schematic side view of a surface cleaning station.

FIG. 16 is a schematic top view of a surface cleaning station.

FIG. 17 is a schematic side view of a flat panel display device.

FIG. 18 is a schematic side view of an alternative surface cleaning station.

FIG. 19 is a schematic side view of an alternative surface cleaning scheme.

DESCRIPTION OF PARTICULAR EMBODIMENTS

Referring to FIG. 1, foreign material **10** may be removed from a surface **11** of a substrate **12**, by delivering to the foreign material energy **14**, which ablates the foreign material from the surface, i.e., the components of the foreign material dissociate into, e.g., molecules, free radicals, and small particles ("ablation components") which expand and rise above the substrate surface as a cloud **16**.

An input fluid **18** (e.g., an elemental gas (e.g., Cl_2, O_2 O_3, F_2), a mixture of elemental gases (e.g., He and O_2), a gas-phase compound (e.g., CO or CF_4), a mixture of one or more of these gases, or a liquid (flowing or static)) is used to reduce or prevent the ablation components of the foreign material in the cloud from redepositing onto the substrate surface by, e.g., reacting with the ablation components to form simple gases ("reaction products," e.g., gases) or entraining the ablation components in a gas flow away from the substrate. The formation of the reaction products is generally associated with the generation of heat and light, some of which may be visible. The ablation components of the foreign material, the reaction products in the cloud, and the volatile compounds formed at the surface are then removed from the vicinity of the substrate, as indicated by arrow **20**, and the surface is left clean.

Reactions in which the foreign material reacts directly with reactive species in the input fluid to form volatile compounds may occur at the surface. Energy **14** may be absorbed by components of the input fluid to generate excited species that react with the foreign material to produce reaction products in the cloud or volatile compounds at the surface in the absence of ablation.

By careful control of the process, a variety of foreign materials may be efficiently removed without damage to the surface and features on the surface. Careful selection of certain reaction conditions ensures that most of the ablation components in the cloud completely react with reactive species in the input gas, instead of forming particulates or other materials that redeposit onto the substrate surface. The process aspects to be controlled include the form of the delivered energy (e.g., laser radiation possibly augmented by acoustic energy or plasma discharge), the way the energy is delivered (angle of incidence of the energy beam, energy density and distribution, wavelength distribution, shape and dimension of the irradiated region of foreign material, beam pulse rate), the input fluid (composition, temperature, velocity, flow volume, angle of delivery, delivery location, gas pressure), the removal of the cloud (entraining gas flow, vacuum exhaust), and the reaction conditions (submerged reactions; substrate pretreatment; reaction chamber conditions; substrate temperature; input fluid temperature, pressure, and velocity; number of scans and pattern of scanning; catalysts).

Proper selection of parameters minimizes heating and other undesirable conditions which could damage the surface or features on the surface. Parameters can be selected for optimal targeted removal of specific foreign material.

Intended

M

Foreign Material in General

Foreign material on substrates includes, e.g., contaminants, organic layers, and residues.

Contaminants

Many contaminants found on substrates are inherent to processing environments; these include particulates from the air (e.g., dust, lint, gas-phase oxides, metals, water, atmospheric debris and stains) and from process technicians (e.g., skin). The steps required for processing a substrate into a finished product also contribute to surface contamination (e.g.: polymer residues, photoresist layers, and silicon dust from integrated circuit processing; copper, aluminum, permalloy, epoxy, and phenolic from printed circuit fabrication; and oxides and glass particles from flat panel display manufacturing).

While most contaminants found on substrates are organic molecules (including: carbon, hydrogen, oxygen, nitrogen, sulfur; trace metals, such as iron and sodium; and trace oxides), other contaminants may be present, such as metals (e.g., copper, aluminum, brass, and iron), silicon, oxides (e.g., silicon oxide and aluminum oxide), and minerals (e.g., gypsum). Each type of contaminant may require selection of different parameters for efficient removal.

Organic Layers

An important application of surface cleaning is the removal of organic layers (e.g., polymers, photoresist, polyamide, polyimide and ink) from surfaces. Organic layers typically have thicknesses that range from 0.2 μm to 25 μm, and compared with residues and contaminants, organic layers involve much greater volumes of material to be removed. Therefore, a relatively greater quantity of input gas is required to react with and/or entrain the ablated organic material. Ablation provides a convenient way to efficiently remove organic layers by converting the ablated solid organic material into a large volume of gas (larger than when in solid form). In gaseous form, the ablated organic material can more easily mix with the reactive species in the

back to aid the reactant to react with the foreign material. The beam may be a laser beam with a long, narrow cross-section and include ultra-violet radiation in the wavelength range 4 nm to 380 nm. The beam cross-section may be at least as long as the surface is wide.

In general, in another aspect, the invention features forming the beam of radiation with a pre-defined non-uniform cross-sectional intensity profile. In implementations, the profile may include a higher intensity central region with lower intensity peripheral regions. The profile may be formed by superimposing light beams of different wavelength, each having a preselected intensity profile, e.g., by frequency multiplying a single laser source; or by superimposing focused and unfocused versions of a source beam. The surrounding lower intensity regions of the profile are formed by a UV floodlamp that produces relatively high energy density light at wavelengths below 200 nm.

In general, in another aspect, the invention features scanning the beam across the surface in more than one scan with less than all of the processing being done in any one scan. In implementations, the total scan time for all scans may be less than the time which would otherwise be required to perform the same processing in a single scan.

In general, in another aspect, the invention features delivering an array of distinct beams of radiation to aid the reactant to react with the foreign material to form the reaction product simultaneously at an array of locations on the surface. In implementations of the invention, the array may be scanned across the surface. The array of distinct beams may be configured to permit complete coverage of the surface by scanning a distance less than the full extent of the surface. A first beam may be split into at least two spaced-apart beams having respective energy densities lower than the energy density of the first beam.

In general, in another aspect of the invention, acoustic energy (e.g., pulsed) is delivered to aid the reactant to react with the foreign material to form the reaction product. In implementations, the acoustic energy may serve to remove particles of foreign material from the surface.

In general, in another aspect of the invention, a plasma discharge is provided to aid the reactant to react with the foreign material to form the reaction product.

In general, in two aspects of the invention, the temperature of the surface is elevated prior to delivering the beam; and a catalyst is provided in the vicinity of the surface.

In general, in another aspect of the invention, the configuration of the flow is arranged so that components of the fluid form reactants in the vicinity of the foreign material.

In general, in other aspects of the invention, the steps of (a) scanning a laser beam across a surface and (b) flowing a reactant gas in the direction of a reaction zone in the vicinity of the intersection of the beam with the surface are used to clean the surface of a semiconductor wafer to remove ion-implanted patterned photoresist; or to remove ink dots placed on semiconductor wafers during a test procedure; or to clean the surface of a thin-film magnetic disk read-write head substrate to remove patterned photoresist; or to clean a flat panel display substrate to remove a film of an organic material (e.g., polyimide) from selected areas; or to clean disks used in the manufacture of compact disks to remove organic and/or metal films.

Ion-implanted photoresist may be removed by scanning the laser beam until a top portion of the ion-implanted photoresist is removed, wetting the ion-implanted photoresist with a liquid comprising a liquid reactant, and applying laser energy to the ion-implanted photoresist through the liquid. Wetting may comprise flowing a liquid over the ion-implanted photoresist or immersing the ion-implanted photoresist in a bath containing the liquid.

Implementations of the invention may include the following features. The surface of the substrate may be held in a non-horizontal orientation (e.g., upside down or vertically) during processing. The surface to be processed may be treated continuously. The substrate may be continuous and elongated, e.g., as a wire or tape, or may be in consecutive pieces that are placed on a moving conveyor belt or web, and the processing may be performed continuously along the length of the web.

Among the advantages of the invention are the following.

Surface cleaning converts foreign material on a substrate surface from a solid to a gas form. This makes it easier to transport the foreign material from the surface. High efficiency is achieved by selecting parameters which are tuned for the particular type of foreign material that is to be removed, maximizing the energy transfer to the foreign material and minimizing the energy transfer, and thus the possibility of damage (e.g., due to heat, shock wave, or other effects), to circuitry and other features on the surface, and to the surface itself.

Surface cleaning according to the invention provides important advantages to the semiconductor industry. Cleaning with radiant energy and low volumes of reactant gases results in low volumes of relatively harmless product of oxidation or other types of reaction products. This reduces the environmental impact of the cleaning process and increases operator safety, compared with the standard wafer cleaning practice in which large volumes of concentrated acids, bases, organic solvents, and even larger volumes of contaminated rinse water are used. In addition, we have estimated that the overall cleaning cost for, e.g., wafer cleaning will be one-twentieth of the cost associated with conventional cleaning methods. The invention enables rapid surface cleaning, with an estimated cleaning time for a 200 mm diameter wafer of between 30 and 60 seconds, depending upon the nature of the foreign material on the wafer surface. Also, surface cleaning according to the invention eliminates the problems associated with conventional plasma and early UV cleaning methods such as electrical fields, induced currents and high energy reactions which are potentially harmful to semiconductor devices and substrates.

The size of the smallest particle capable of causing a defect in an integrated circuit is decreasing as the semiconductor industry pushes for smaller circuit dimensions. As particle sizes decrease, surface cleaning techniques that simply rely on breaking adhesive forces to physically remove these small particles become less efficient, because the energy required to remove the contaminants becomes comparable to the energy sufficient to damage a surface (e.g., 10,000 psi of pressure is not sufficient to remove 0.25 micron particles from a semiconductor surface). Surface cleaning according to the invention, on the other hand, can remove particles having a dimension of 0.25 μm and smaller from a surface without damage.

Other advantages and features will become apparent from the following description and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic sectional side view of a substrate being cleaned.

FIG. 2 is a perspective view of a beam expanding system.

FIG. 2A is a schematic side view of a beam directing technique.